Proposed Alternative Method for Calculating Emissions from Hydraulic Fracturing Operations

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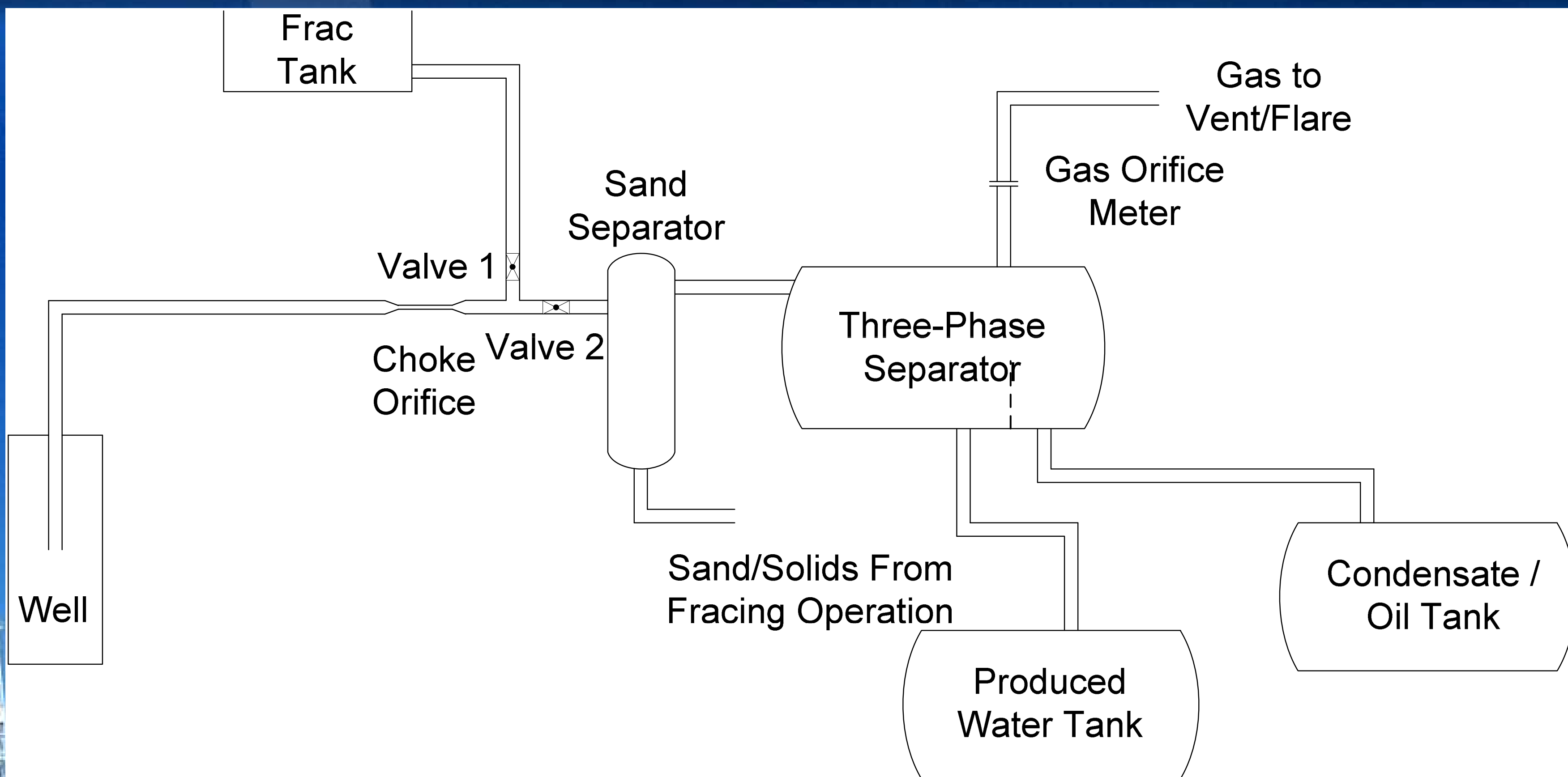
Outline

- Background on Reporting Greenhouse Gas (GHG) Emissions
- Analysis of EPA Equation
- Discussion of Alternate Method
- Analysis of Alternate Method as Confirmational Tool
- Analysis of Alternate Method as Predictive Tool
- Comparison of Alternate Model to Existing EPA Equation

Background

- EPA Mandatory Greenhouse Gas Reporting Rule
  - 40 CFR 98 Subpart W: Petroleum and Natural Gas Systems
  - Includes emission estimation methodologies and reporting requirements
  - GHG emissions include N_2O, CH_4 and CO_2 during flow back after hydraulic fracturing
- Hydraulic Fracturing: Fracturing rock using pressurized liquid to stimulate a well to maximize oil and gas extraction
  - Flowback: Process of removal of spent fluids (wastewater, produced water, etc.) prior to well production

Flow Back Process Flow Diagram



Three Phase Separator

Frac, Water and Oil Tanks

Produced Gas Flow Meter

Produced Gas Flare

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Existing EPA Methodology (1 of 2)

- Option 1: Measure and record GHG emissions from each fractured well

- Option 2: Measure and record GHG emissions from subset of wells, and extrapolate to other wells
  - Measurements cost on the order of $ 5,000 per day at each site

- Option 3: Calculate emissions in lieu of performing measurements

Existing EPA Methodology (2 of 2)

- Option #3: EPA Equations W-11A and W-11B

- Subsonic Flow (W-11A)

$$FR_a = 1.27x10^5 * A * \sqrt{3430 * T_u * \left[\left(\frac{P_2}{P_1}\right)^{1.515} - \left(\frac{P_2}{P_1}\right)^{1.758}\right]}$$

- Sonic Flow (W-11B)

$$FR_a = 1.27x10^5 * A * \sqrt{187.08 * T_u}$$

- Both equations calculate an actual volumetric gas rate
- Assume sonic flow applies ($P_1/P_2 > 2$) and use Eq. W-11B

Why Explore Alternatives to EPA Equations?

- EPA Equations
  - Appear to be derived from ideal gas law
  - Assume single-phase, methane gas
- Flowback following hydraulic fracturing
  - Multiple fluid phases (gas, oil, water)
  - Variable flow rate
  - Variable composition
- Result: EPA Equation W-11B typically overestimates GHG emissions

Alternative: Empirically Derived Relationships

- Gilbert-type Correlation (1954)
  - Multiphase flow through wellhead choke
  - General form

$$P = \frac{c * Q_L * R^a}{S^b}$$

P = upstream pressure (psia)
Q_L = gross liquid rate (barrels per day)
R = gas to liquid ratio (Mscf/bbl)
S = choke size (1/64” increments)

Empirical Data Analysis

•Step 1: Collect measured data for upstream pressure, choke size, and oil, water and gas production rates

•Step 2: Convert Gilbert-type correlation to linear form

$$\boldsymbol{ln\,(P) - \; ln\,(Q_L) = \; ln\,c + a * ln\,(R) - \; b * ln\,(S)}$$

•Step 3: Solve for a/b/c coefficients using multivariable linear regression

•Step 4: Rearrange and solve for gas rate

$$\boldsymbol{Q_G = Q_L * \left(\frac{P * S^b}{c * Q_L}\right)^{1/a}}$$

•Step 5: Compare measured gas rate to calculated gas rate

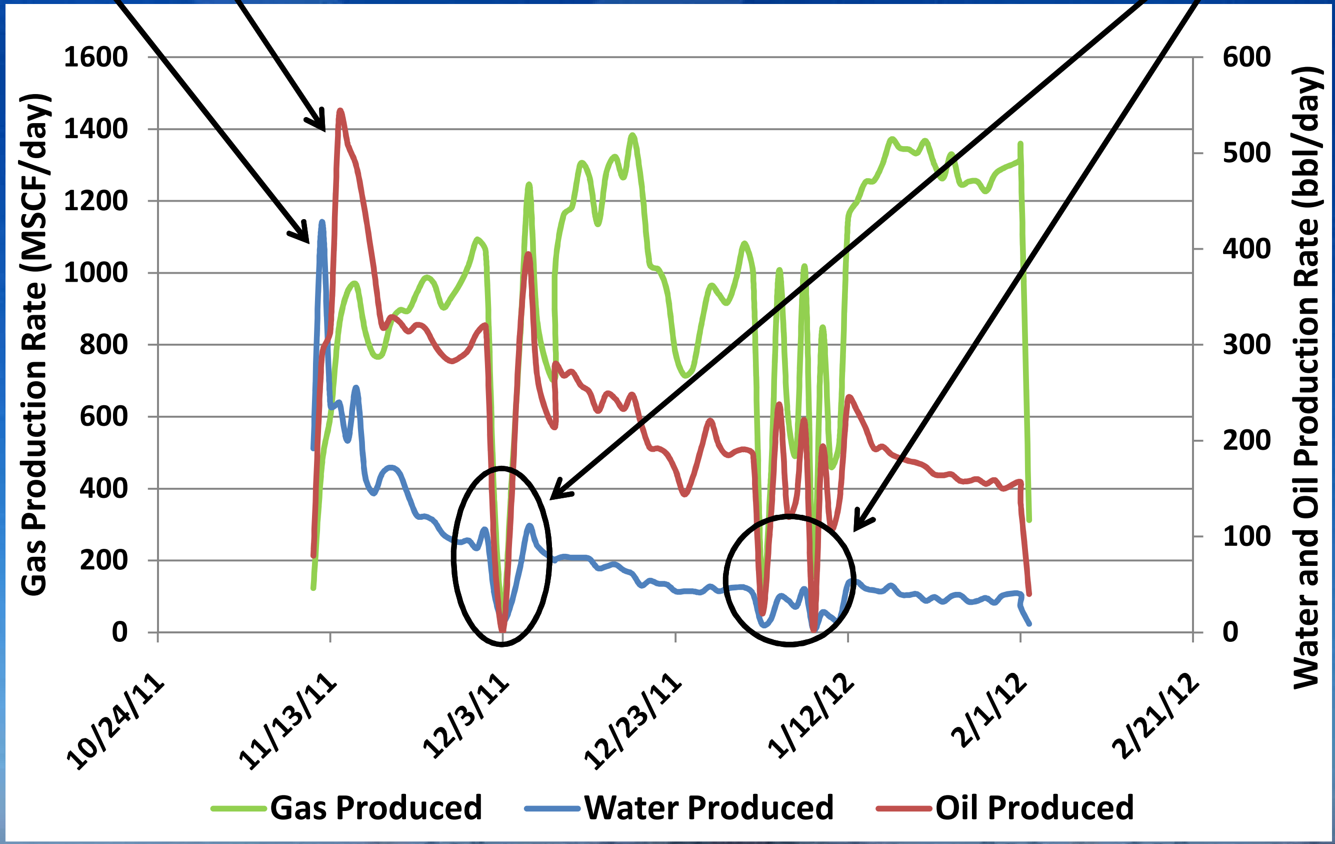
Site-Specific Data Collection

- 13 total flowback operations
  - Ten high flow rate operations
  - Three low flow rate operations
- Measured data recorded hourly
  - Tubing pressure, choke size, cumulative gas/oil/water produced
- Removed periods of atypical operation from analysis

Atypical Operation: Examples

No multiphase flow

No flow



Analysis of Site-Specific Data

- Calculate seven-day averages for collected data
    - Tubing pressure (psia)
    - Choke size (1/64" increments)
    - Daily gas production (Mscf/day)
    - Daily water production (bbl/day)
    - Daily oil production (bbl/day)

- Calculate gas to oil ratio, gross liquid rate for seven-day averages

- Regress data to calculate a/b/c coefficients and compare calculated gas production to measured gas production

Results of Site-Specific Data Analysis

Site	Measured Cumulative Gas Volume (MMscf)	Predicted Cumulative Gas Volume Site-Specific Correlation (MMscf)	Error (%)
Noble Well 1	81	88	9
Noble Well 2	100	97	-2
Noble Well 3	58	58	-1
Noble Well 4	27	29	7
Noble Well 5	37	41	9
Noble Well 6	79	79	0
Noble Well 7	144	149	4
Noble Well 8	62	66	7
Noble Well 9	59	66	12
Noble Well 10	47	49	3
Field Total / Error Value	**694**	**722**	**4**

- Gilbert-type correlation provided excellent results when using site-specific coefficients
- Valid for use as confirmational tool

Extend Analysis to Entire Field

- Analysis of site-specific data only confirms that the correlation is valid when using site-specific coefficients

- Analysis of field-wide data was necessary to assess accuracy of correlation as predictive tool for other wells in the same field

Analysis of Field-Wide Data

- Created composite data set of seven-day averages from ten long-term flowback operations

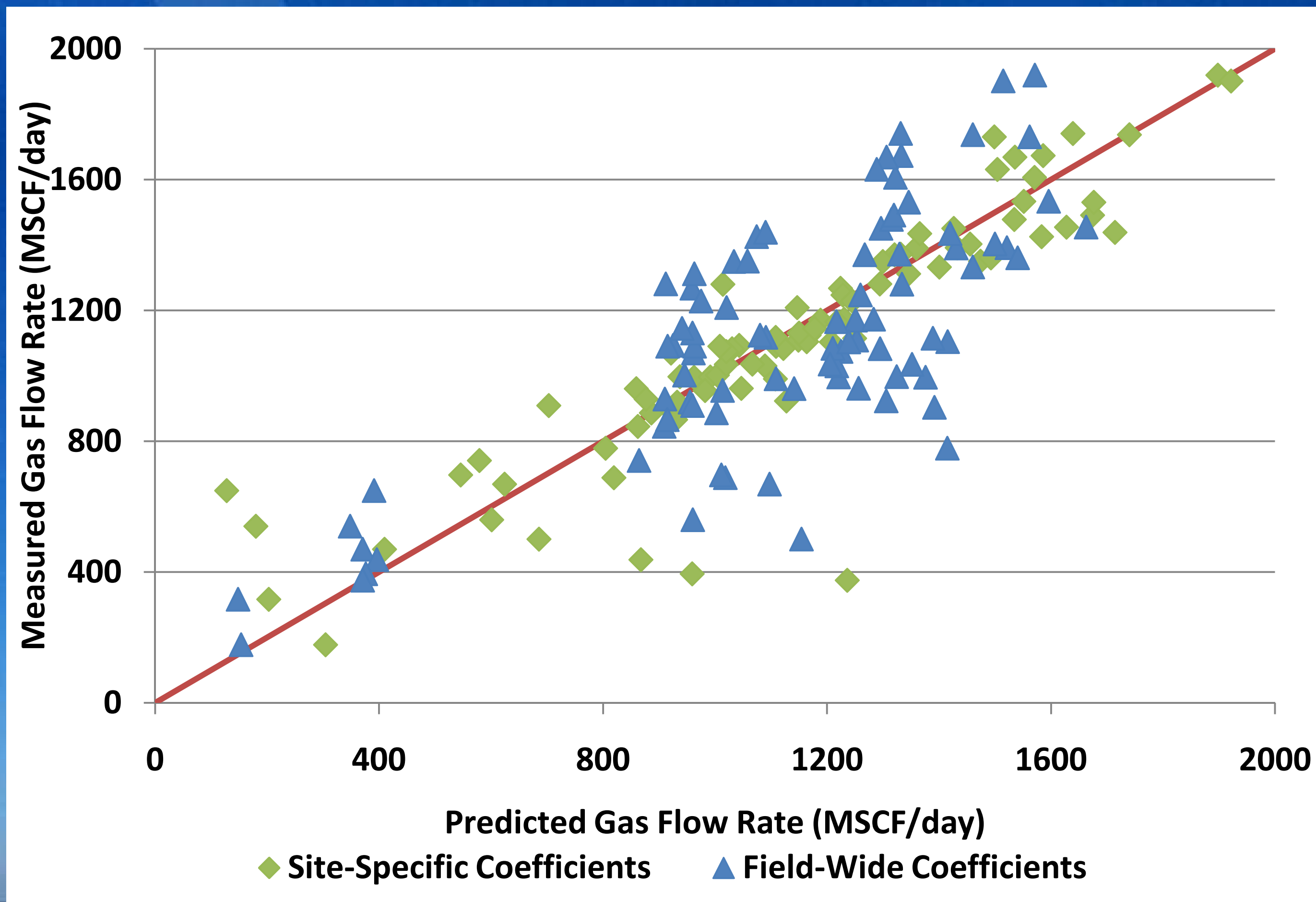
- Regressed one single set of a/b/c coefficients using data from all ten, high flow rate wells

Results of Field-Wide Data Analysis

Site	Measured Cumulative Gas Volume (MMscf)	Predicted Cumulative Gas Volume Field-Wide Correlation (MMscf)	Error (%)
Noble Well 1	81	100	24
Noble Well 2	100	92	-8
Noble Well 3	58	46	-20
Noble Well 4	27	20	-25
Noble Well 5	37	36	-3
Noble Well 6	79	89	12
Noble Well 7	144	130	-9
Noble Well 8	62	75	21
Noble Well 9	59	84	43
Noble Well 10	47	46	-3
Field Total / Error Value	**694**	**718**	**3**

- Using field-regressed coefficients is satisfactory
- More variability with field-wide than site-specific coefficients

Parity Plot


2000
1600
1200
800
400
0
Measured Gas Flow Rate (MSCF/day)
0
400
800
1200
1600
2000
Predicted Gas Flow Rate (MSCF/day)
Site-Specific Coefficients
Field-Wide Coefficients

EPA Equation W-11B

- Equation W-11B calculates emissions as a function of average upstream temperature and choke size
- Equation W-11B has a consistent, high bias compared to measured emissions

Site	Cumulative Measured Gas Volume (MMscf)	EPA Eq. W-11B (MMscf)	EPA Eq. W-11B Error (%)
Noble Well 1	81	188	133
Noble Well 2	100	177	78
Noble Well 3	58	94	61
Noble Well 4	27	59	118
Noble Well 5	37	77	106
Noble Well 6	79	177	123
Noble Well 7	144	214	49
Noble Well 8	62	152	144
Noble Well 9	59	145	145
Noble Well 10	47	90	89
Field Total / Error Value	**694**	**1373**	**98**

Comparison of Empirical Methods with Equation W-11B

Site	Measured Cumulative Gas Volume (MMscf)	Predicted Cumulative Gas Volume Site-Specific Correlation (MMscf)	Predicted Cumulative Gas Volume Field-Wide Correlation (MMscf)	EPA Eq. W-11B (MMscf)
Noble Well 1	81	88	100	188
Noble Well 2	100	97	92	177
Noble Well 3	58	58	46	94
Noble Well 4	27	29	20	59
Noble Well 5	37	41	36	77
Noble Well 6	79	79	89	177
Noble Well 7	144	149	130	214
Noble Well 8	62	66	75	152
Noble Well 9	59	66	84	145
Noble Well 10	47	49	46	90
Field Total	**694**	**722**	**718**	**1373**

- Empirical method was consistently more accurate than EPA Equation W-11B for these data

Summary

- Gilbert-type correlation can be used to predict overall volume of gas produced during flowback operations
- Gilbert-type correlation was sufficiently accurate at site-specific and field-wide levels
    - Variables required: choke size, tubing pressure, total produced liquid
- Gilbert-type correlation is more complicated than Equation W-11B
    - Requires linear regression
    - Requires engineering judgment to exclude data from periods of atypical operations
- EPA Equation W-11B consistently overestimated overall volume of gas produced for the wells studied
- Predictive correlation should be tested and validated using data from other formations to confirm its applicability in other formations and fields

Acknowledgements

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